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This report describes work that has been performed within the last year on the modeling of the disturbed magnetospheric magnetic field. The reasons for developing quantitative magnetospheric models are twofold: first, there are many model users who have "practical" needs. Their requirements are to specify and to predict such things as: radiation dose in the earth orbital environment, fluctuations in ionospheric electron density, variations in the earth's upper atmosphere density, and the impact of magnetic storms on loading changes in

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electrical power grids. The second set of model users have technical and scientific needs. They use the magnetic field models in studies of other magnetospheric, ionospheric, and upper atmospheric phenomena, or to understand the interactions of magnetospheric magnetic and electric fields with particle populations. This report should be the last of a series quantitatively describing the magnetospheric magnetic field. Some of the history of the magnetic field work that leads to the efforts pursued this last year is described.

Final Report

MAGNETOSPHERIC MAGNETIC FIELD MODELING

FEBRUARY 1979   F44620-75-C-0033
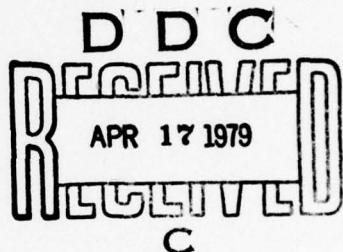
Principal Investigator: W. P. Olson

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INTRODUCTION

This report describes work that has been performed within the last year on
the modeling of the disturbed magnetospheric magnetic field. In previous
reports, the reasons for developing quantitative magnetospheric models have
been discussed in detail. Basically they are twofold; first there are many
model users who have "practical" needs. Such users are not interested in the
origin of the model, but only in its accuracy. Their requirements are to
specify and to predict such things as; radiation dose for man and hardware
components in the earth orbital environment, fluctuations in ionospheric
electron density on radio communications, the effects of variations in the
earth's upper atmosphere density on satellite orbital decay and the accurate
targeting of ballistic missiles, and the impact of magnetic storms on loading
changes in electrical power grids at mid and high latitudes. The other set
of model users have technical and scientific needs. They either use the
magnetic field models to help in their studies of other magnetospheric, iono-
spheric, and upper atmospheric phenomena, or directly to help them to understand
the interactions of magnetospheric magnetic and electric fields with the high
and low energy particle populations resident there.

We have worked on this problem of quantitatively describing the magnetospheric
magnetic field for several years. We believe that with some minor exceptions,
this report should be the last of a series describing that work. It is
therefore appropriate to document here some of the history of the magnetic

field work that lead to the efforts pursued this last year. They are described

in some detail before the work of the current contract period is discussed.

Section 2

HISTORICAL PERSPECTIVE

2.1 EARLY QUANTITATIVE MAGNETIC FIELD MODELING WORK

There were several reasons for beginning this work a few years ago. At that time the existing magnetic field models seemed to be in error in several ways and could not adequately account for several observed magnetospheric features and phenomena. The solar cosmic ray cutoff problem had been well described and it appeared that these energetic solar particles could find their way to the earth's surface to much lower latitudes (about 6-8 degrees) than those expected if the interaction between the particles and the geomagnetic field was simply in terms of the Lorentz force acting on the particle. This discrepancy gave rise to several papers which suggested that various diffusion processes were present in the earth's magnetosphere (e.g., see Pfitzer, 1979). The lack of understanding of the problem was contained in the various diffusion parameters which were suggested. At about the same time, M. Sugiura and his colleagues were reporting that the observed total magnetic field in the inner magnetosphere was depressed (Sugiura, 1973). That is, its value was less than that given simply by the earth's main dipolar field. This is what naively might have been expected from the existence of a quiet time ring current since the low energy plasma in the magnetosphere is of course diamagnetic. However, the early models did not include this feature. In fact, in this region the models suggested that the quiet time field was enhanced. Many observations were being made which indicated that the magnetic field topology was much less dipolar than suggested by the early models. That is, the field lines were observed to extend much farther out into the magnetosphere than the

models predicted. A model that took into account the depressed nature of the magnetic field in the inner magnetosphere caused by the presence of the distributed ring current might therefore explain both of these features (the cosmic ray cutoff problem, and the extended field lines) and several other recently observed particle and field properties.

One reason that such a model had not been attempted earlier was a result of the traditional usage of scalar potentials in the quantitative description of the magnetic field. This was a carryover of the formalism which had been traditionally used to describe the earth's main magnetic field. The main magnetic field has been traditionally described in terms of associated Legendre polynomials. Such series represent a scalar magnetic potential which can be differentiated to yield the components of the earth's main magnetic field. This scalar description can be used only at points which are outside of the source region of the magnetic field, thus the scalar potential cannot be used in the inner magnetosphere to describe the magnetic field resulting from the quiet time ring current which persists in that region. Thus the use of the scalar potential had to be abandoned. In its place, a representation that allowed $\nabla \times \overline{B}$ to be non zero was required.

Another problem was how to represent currents that flow in a distributed way through a large volume. Ideally, one would like to be able to write down analytically a function describing the currents. However, owing to the complex topology of the currents flowing in the ring and even moreso in the tail regions, this was not attempted. Instead, wires were used to represent the distributed current system. Nests of wire were placed in both the inner

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magnetosphere and throughout the tail to represent the quiet time ring and
the tail current systems. When the integration was done over the current
systems using the Biot-Savart law, it was required that the location of
points in between the wires was chosen such that the contribution to the fields
there from the two closest wires cancelled out. This removed the problem of
having abnormally large magnetic fields produced by the wires (this method
would of course be tested later by comparing the value of $\nabla X \overline{B}$ with the input
currents to see how well they agreed).

The procedure for determining the strengths and locations of the
currents flowing in the wires was non-trivial because no direct observational
data on these currents exist. Rather, it is the magnetic fields they produce
that have been documented fairly well throughout the magnetosphere. The
procedure was therefore rather cumbersome and involved integrating over a
set of provisional current loops and finding the resulting magnetic field at
many points throughout the magnetosphere. These magnetic field values were
compared with many sets of observational data and differences noted. The
currents in the wires were then adjusted along with their location until
a satisfactory representation of the magnetic field resulted. What is said
here in a few sentences actually took several months of hard work to
accomplish. A more detailed description of the procedures for quantitatively
representing the distributed currents is provided in Appendix A. The result
was a description of the magnetic field at approximately 1500 points spaced
throughout the magnetosphere. These points were then input to a very flexible
least squares fitting subroutine which permits the user to arbitrarily use any
set of linearly independent functions in the form of a series to be used to
describe the data. The particular series chosen here, of course, had the

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added requirement that its curl be allowed to be non-zero. The final series

representation for this first model of the total magnetospheric magnetic

field based on the distributed current flowing in the inner magnetosphere and

tail included power series terms as a function of location, multiplied in some cases

by an exponential function. The exponential function looks something like

the error function and made it possible to accurately describe the build-up

and decay of the ring current portion of the field as a function of increasing

geocentric distance. The topology of the magnetospheric magnetic field in the

noon-midnight meridian plane as suggested by the model is shown in Figure 1.

The first model had several immediate successes. It of course provided the

most accurate ΔB contour plots to date as it was in part based on those

observations provided by Sugiura and his colleagues. A comparison of observed

and model generated ΔB contours can be made by observing Figures 2 and 3.

Most notably, the depressed field regions in the inner magnetosphere contained

in this model resolved the apparent discrepancy regarding the cutoff latitudes

for solar cosmic ray penetration. Thus, although some problems remained, which

would be resolved in future magnetic field models, these results suggested

that no diffusion process was really involved and that rather, all that was

needed was an accurate description of the total magnetospheric magnetic field.

The "snap shot" of a magnetic field line provided by a barium release provides

another test of magnetic field model. The NASA/MPI barium release resulted in

in a magnetic field model constructed specifically for that release.

When tested with this barium release data, our early model was more

successful than the one developed specifically for that release (see Figure 4).

Other early successes of the models included the correct description of the

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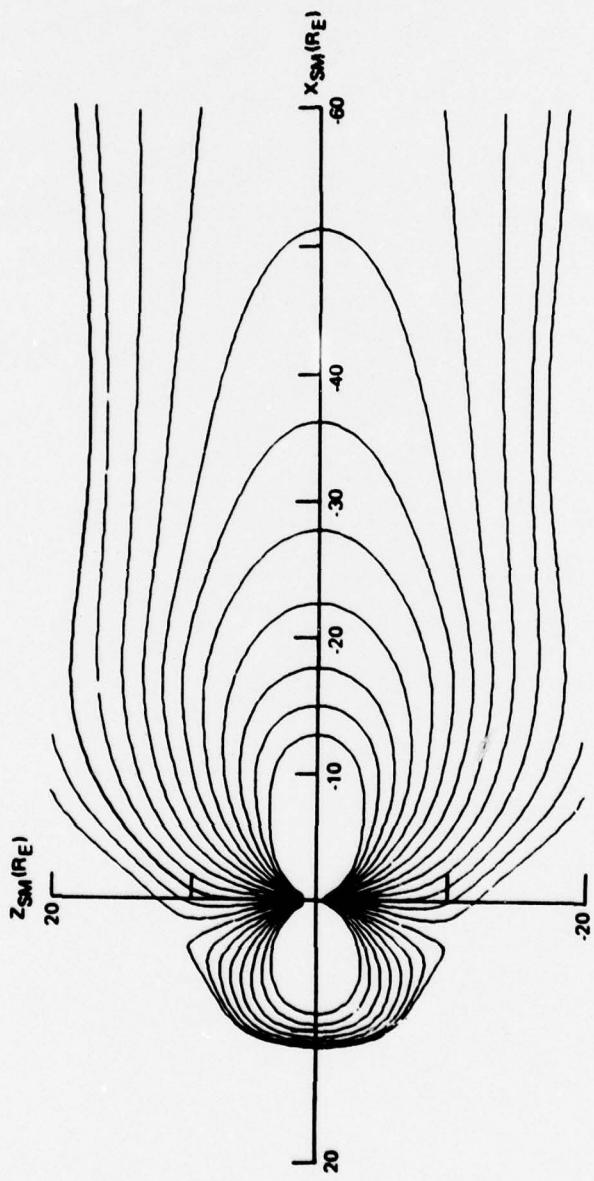
Figure 1. Field line in the noon-midnight meridian plane from a magnetic latitude of 70° to 90° in steps of 2°.
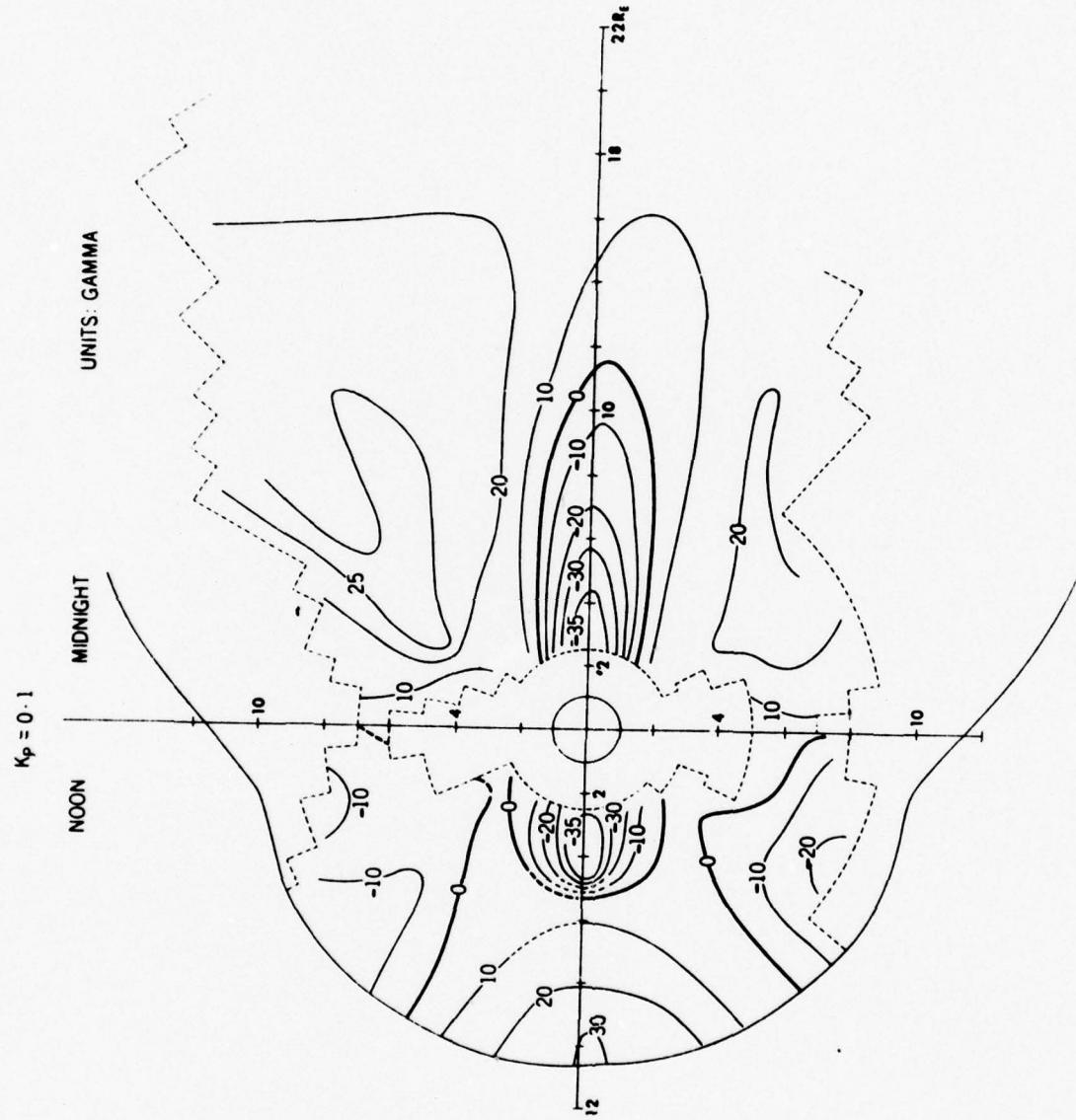
Figure 2. ΔB contours in the noon-midnight meridian plane as determined by Sugiura and Poros (1973)

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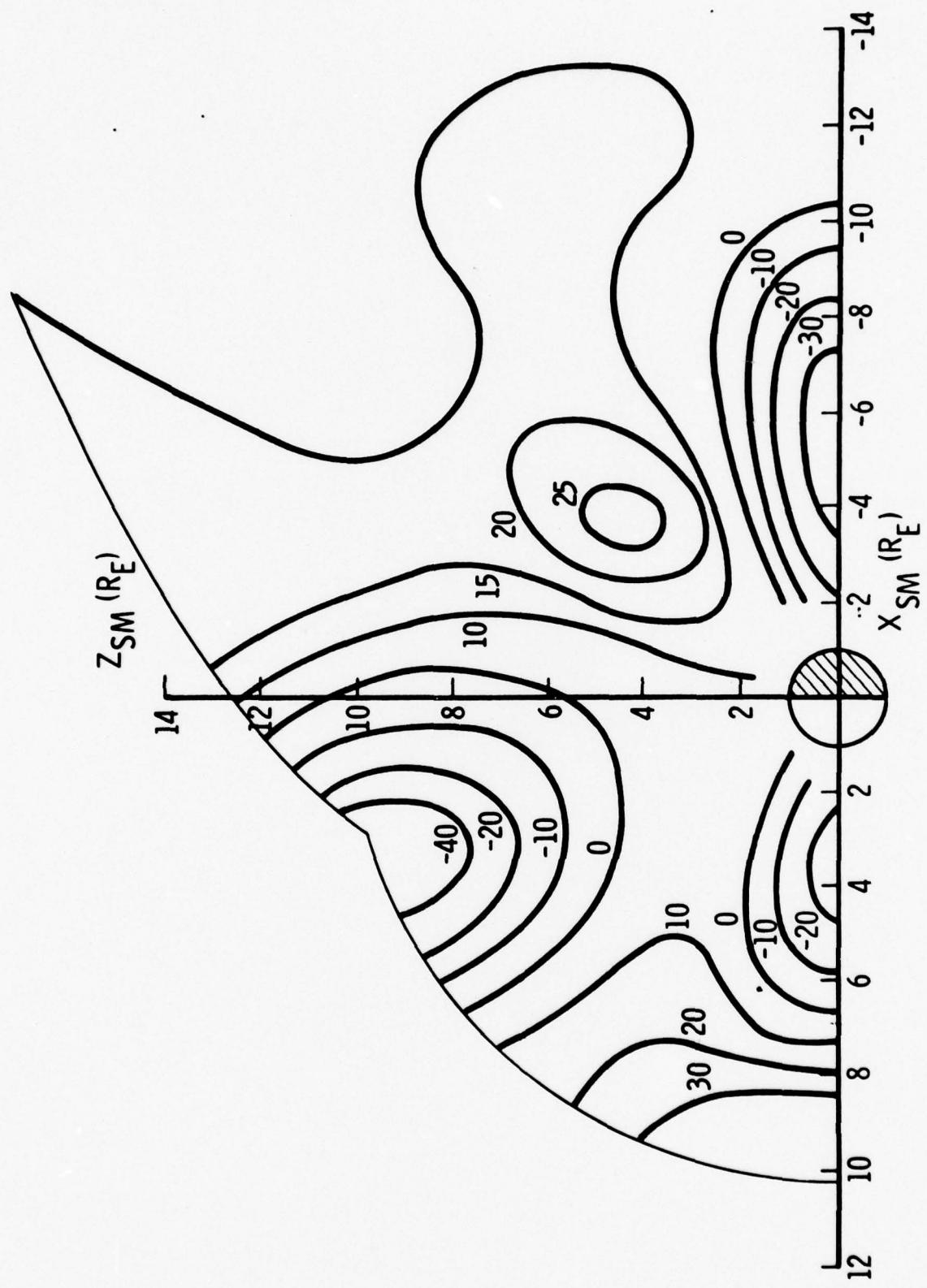
Figure 3. Contours of constant ΔB in the noon-midnight meridian plane.

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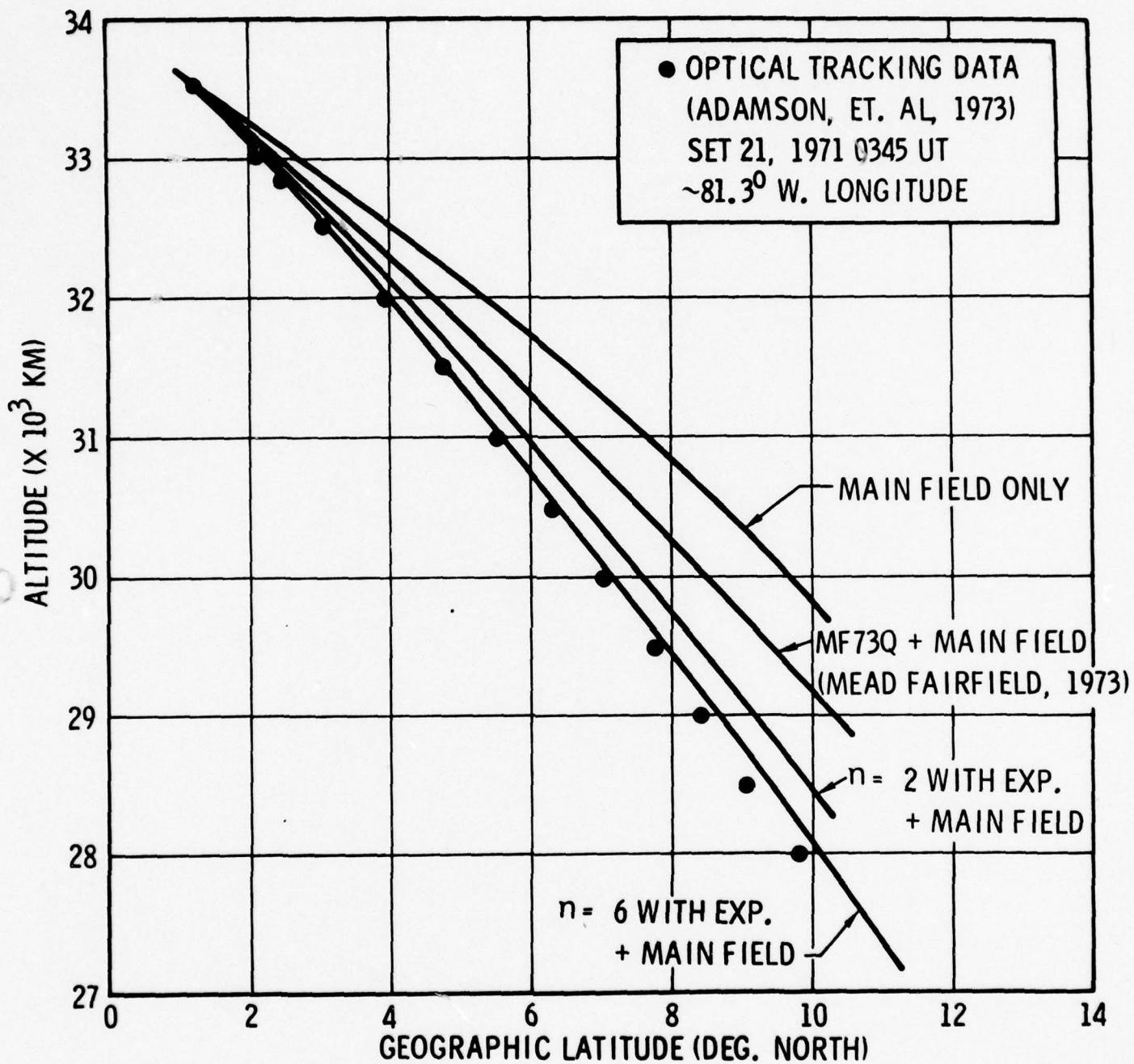
Figure 4. Field line shape as determined by optical tracking of a barium cloud
(Adamson, et al., 1973) and from quantitative field models.

high latitude cutoff for the trapping boundary of lower energy particles (see Figure 5), and several other magnetic field topology features especially as observed at geosynchronous orbit.

2.2 EXTENSIONS OF THE EARLY WORK

This early model was limited in at least two ways. First of all, it described only the "symmetric" magnetosphere with the solar wind incident perpendicular to the axis of the earth's internal dipole magnetic field. Also the model was restricted to represent only "quiet" conditions. It was decided that the first way to extend the model was to include "tilt" effects. The model would then be capable of describing the total magnetospheric magnetic field for all possible geometries of solar wind-dipole axis during quiet magnetic conditions. This alternative was chosen over the other (extending the model to disturbed periods) because of the relatively large amount of quiet time data available.

It has been our policy in all modeling efforts to provide the models to everyone who might wish to use them, and to hear back from every user any comments or criticisms of the models. By the time work was begun on the tilted model, we had heard from many users of their experiences with the original model. There appeared to be only two complaints. First, the magnetic field in the subsolar region was abnormally large. This was simply the result of our least square fittings procedures and the fact that not many points had been used in that region. This problem has been corrected in all future models. The second problem concerned an abnormally large magnetic field at about 13 earth radii back in the tail of the magnetosphere. This problem was not resolved until we understood better how to develop the tilted magnetic field model. It then turned out that the reason for the problem was that we had too faith-

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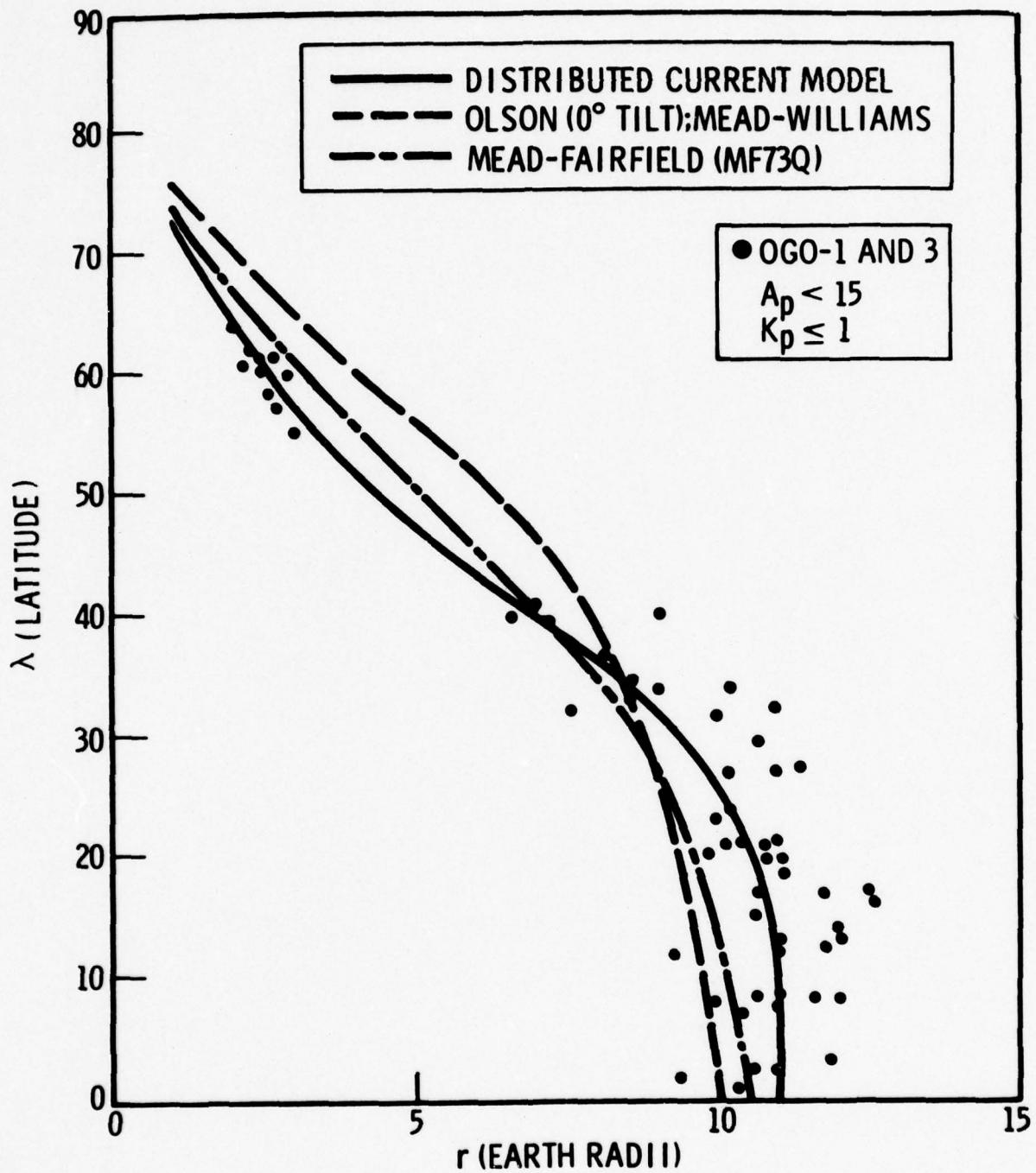
Figure 5. Latitude dependence of the 600 keV electron trapping boundary
at local noon.

fully tried to reproduce Sugiura's ΔB contours. His contour plots were averaged over all tilt angles (the "tilt angle", μ, is the complement of the angle between the solar wind flow vector and the earth's dipole moment vector). The actual contour for $\mu = 0$ is quite different from the contours for $\mu = \pm 35°$ tilt. The ΔB contours for 0° and 35° tilt are shown in Figures 6 and 7. It is seen why averaging over all tilts will not give the same contours as the 0° tilt case. The important lesson we learned was that the zero value of a symmetric function does not necessarily equal to the average value over some interval centered about zero.

The primary data sets for comparing the tilted loop currents with observations were provided by geosynchronous satellite magnetometers. When the final results of the model were compared with the daily variation in the three components of the vector field observed at geosynchronous orbit, they were found to be in excellent agreement. In fact one investigator changed the values of the offsets in the horizontal component for his magnetometer based on the predictions of this model. The model was also used to re-determine the solar cosmic ray cutoff. It was found that some of the earlier problems in the dawn/dusk meridian region were now resolved. With this model the access of solar cosmic rays to geosynchronous orbit was also now in good agreement with experimental observations.

Since part of the modeling effort is the verification of the models using new data, an extensive study of the cosmic ray cutoff problem was initiated during this contract period using the tilt dependent model. Cutoff values for over 600 polar crossings were determined. These cutoffs were organized as a

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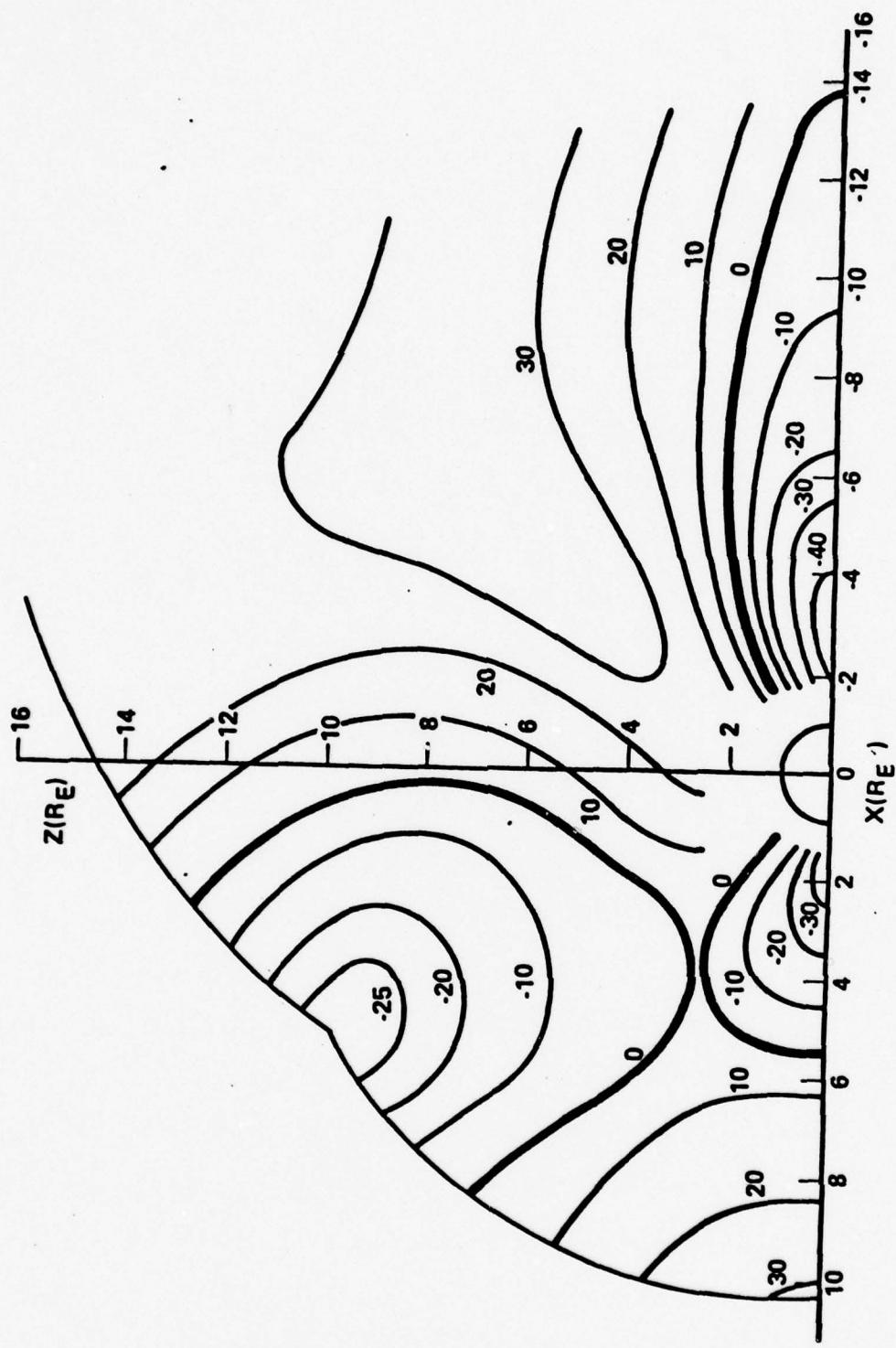
Figure 6. ΔB in the noon-midnight meridian plane (tilt = 0°)

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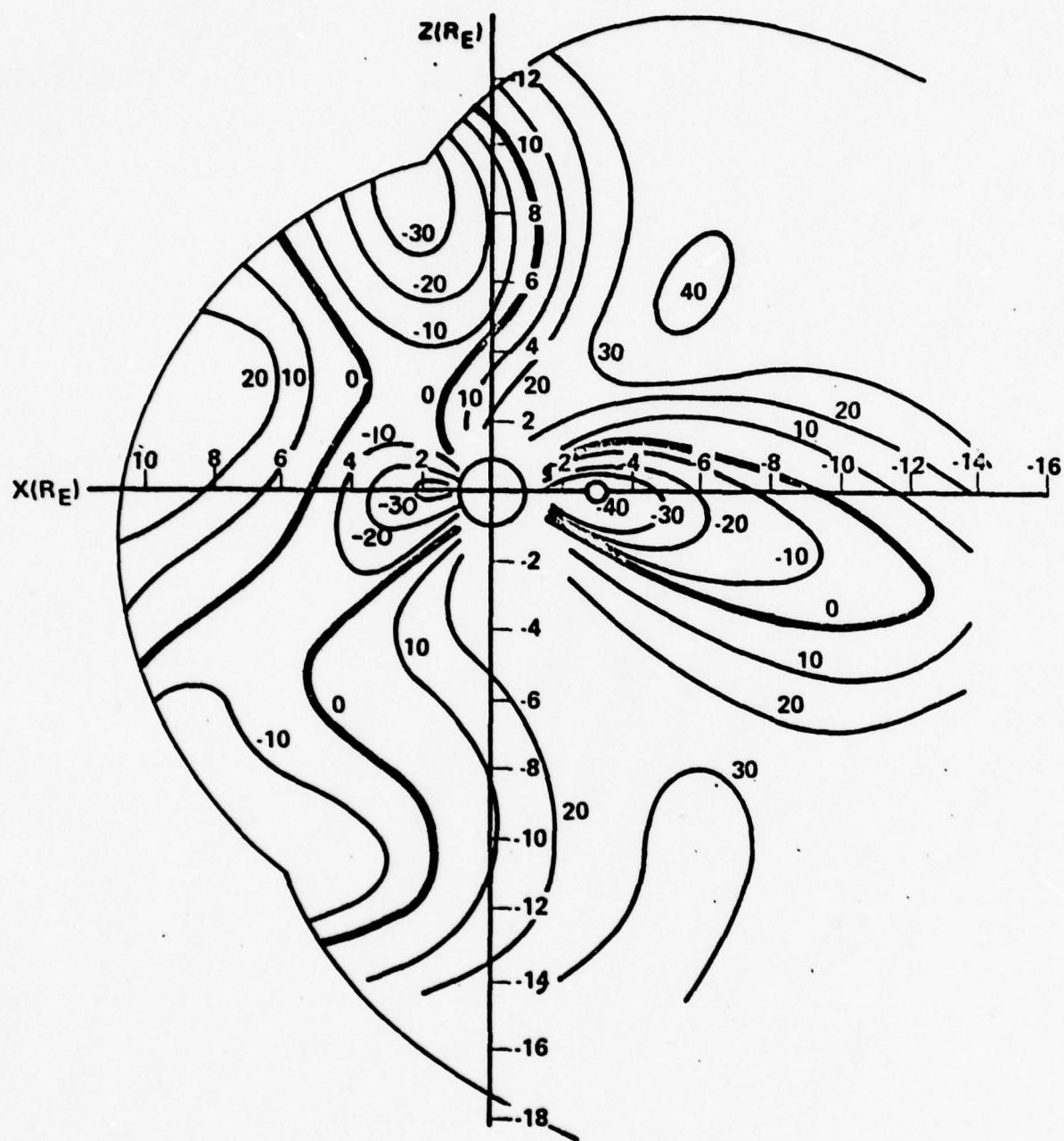
Figure 7. ΔB in noon-midnight meridian plane (tilt = 35°)

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function of tilt angle and K_p. Using least squares fitting procedures it was shown that any tilt dependence in the solar cosmic ray cutoff data was small. This agreed well with model calculations. Table 1 gives the present as well as some of the older model calculations. Table 2 shows the excellent agreement of the current model calculations with the experimental data. Note that although the reuslts using the tilt dependent model were included in the historical part of the report, they were performed during the current period of performance.

One of the limitations of this tilted model was that to this point in time it had been fitted with data only in the earth's inner magnetosphere. Therefore, it could be used only to describe field topology and processes that occurred within geocentric distances of about 13 earth radii. It was this model that was used by the National Space Sciences Data Center to select the optimal final orbit for GEOS-1 after it had suffered an inadvertent launch anomaly.

The final extension of the magnetic field modeling work prior to this year's activities concerned re-fitting the tilted data so that input data points out to 60 earth radii in the tail were included. The fit for this model was then good out to lunar orbit. This description of the tail region is necessary if the models are to be used in the study of the magnetospheric substorm. Results showing the field topology to lunar orbit were presented at the Chapman conference on Quantitative Modeling of Magnetospheric Processes, held in La Jolla last September. Part of the financial support for that meeting was provided by AFOSR.

Table 1

CUTOFF DETERMINATIONS USING VARIOUS MODELS

	Gall, et al. 1968	Olson 1970 Model	Olson-Pfitzer 1974 Model	Present Tilt Dependent Model		
Tilt	0	0	0	0	+35	-35
Noon	72	74	69	70	68	68
Midnight	68	69	66	66	65	66
Dawn	--	--	70	67	67	67
Dusk	--	--	71	67	67	67

Table 2

CALCULATED (NEW TILT DEPENDENT MODEL) AND OBSERVED

(BEST FIT FOR TILT = 0 AND K_p = 0) CUTOFFS

	Best Fit Observation Tilt=0, K_p=0	Calculation To Nearest Degree Tilt=0, K_p=0
Noon	70.4 $\pm$ 0.6	70
Midnight	66.4 $\pm$ 0.4	66
Dawn	67.5 $\pm$ 0.9	67
Dusk	67.5 $\pm$ 0.6	67

2.3 USES OF THESE MODELS

Before going on to the work accomplished under the last contract period, it is instructive to consider the several uses that have been made of these models. The final model as just described, represents all three of the major magnetospheric current systems for all angles of incidence of the solar wind on the geomagnetic dipole field. Its region of validity is from the nose of the magnetosphere back into the magnetospheric tail to beyond lunar orbit. As mentioned above, in order to produce the final product it was necessary to understand quite accurately the topology and strength of the current systems distributed throughout the magnetosphere. The topology of the magnetic field calculated using this model is shown in Figure 8. A total understanding of the dynamics of the currents must await the self-consistent particle field work which is now just beginning. However, the work described above shed much light on the nature of these current systems. The quiet time ring current must have its peak value just inside of geosynchronous orbit during quiet times. In the tail, it is necessary that the currents flow around the magneto-pause boundary and return across the plasma sheath region of the tail. This work indicated very strongly that there is no very thin neutral sheet region in the tail, but rather the currents flow throughout the entire thickness of the plasma sheath. Generally, the distributed currents may be thought of as flowing wherever plasma persists in the magnetosphere. The regions which appear to be most significant are (1) the trapping region in the inner magnetosphere which contains the quiet time ring currents and (2) the equatorial region of the tail of the magnetosphere where particles are held as they bounce back and forth along the magnetic field lines between regions of higher magnetic field intensity and gradually work their way across the tail. The low energy particles that populate this plasma sheath region take

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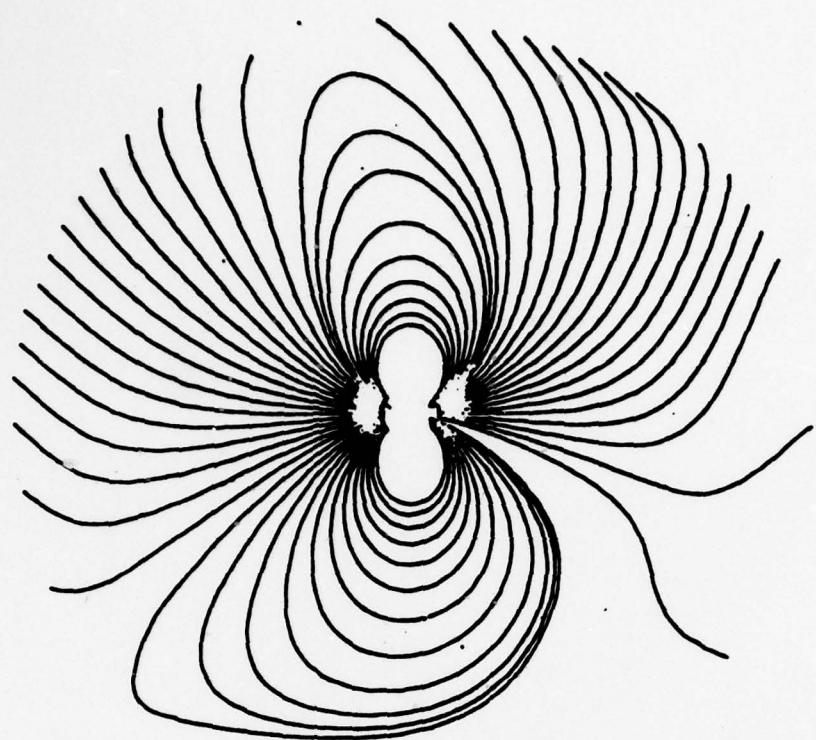
TILT = -35°
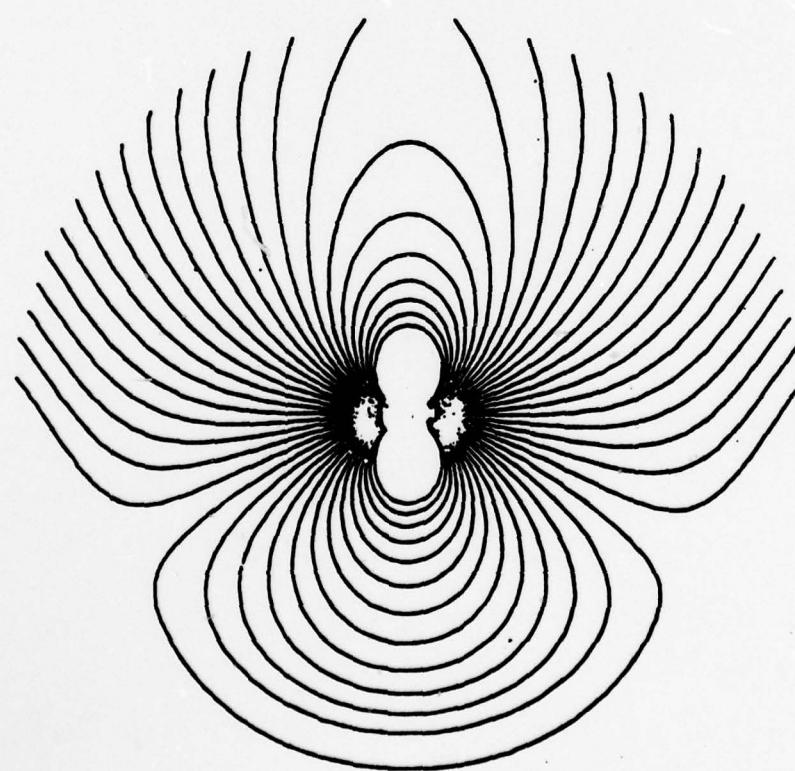
TILT = 0

Figure 8.   Field lines in the noon-midnight meridian plane

approximately three days to move from one flank of the tail to the other.
During this period of time more than a dozen substorms may take place. (A
more detailed discussion on the formation of the distributed currents is
provided in the appendix.) The remaining current system in the magnetosphere,
the magnetopause current, has been well described classically in terms of
pressure balance. At the La Jolla meeting, there were some preliminary descrip-
tions provided concerning the properties of the magnetopause as observed
with the ISEE-A and ISEE-B satellites, which suggest a rather structured
region. What impact this may ultimately have on our understanding of the
magnetopause currents remains to be determined. However, at this point in
time the pressure balance formalism still appears to provide an adequate
description of the magnetopause currents as they grossly affect magnetic field
features throughout the magnetosphere.

These models also forced us to ask questions concerning the access of the solar
wind into the magnetosphere. It seems clear that along the flanks of the tail
magnetosheath particles may enter the magnetosphere proper because of the
gradients of the magnetic field that exist there. As a particle gyrates
around the magnetic field from the magnetosheath into the magnetopause region,
it may find itself, after one revolution, to be in the magnetosphere provided
that its initial "impact" angle with respect to the magnetopause surface is
within a limited range. It has been observed for several years now that
instead of the classical neutral point topology a plasma cleft or cusp geometry
is observed in which plasma may enter into the magnetosphere. In these models,
no attempt was made to input a cusped geometry. However, because of the
imperfect fitting routines, there is not a neutral point but rather an extended

region which separates those field lines which cross the equatorial plane
and those which move far back into the tail.

The models were also used to try to understand the access of high energy
particles to the magnetosphere. The success in describing the access and the
cutoff latitudes for solar cosmic rays has been described above. Generally,
these modeling efforts have lead us to the following conclusions regarding
the topology of the magnetic field. No attempt has been made in these efforts
to "hook" the geomagnetic field to the interplanetary field. Thus, it might
be assumed that the models that have been developed should be described as
"closed." However, because of the imperfect nature of the fitting, some field
lines do not return to the opposite hemisphere, but rather in the "cusp"
region several field lines do wander out of the magnetospheric cavity. From
a practical standpoint, it is probably more important to discuss the topology
of the magnetosphere regarding access of particles. In that sense, the modeling
effort clearly indicates the magnetosphere is open. That is, both low and high
energy particles coming from the sun have access to the inside of the magneto-
sphere. The low energy particles entering the magnetosphere on the day side
may be restricted to move through a "mantle" region which persists only near
the boundary of the magnetospheric tail. However, some other regions allow
low energy particles to precipitate deep into the magnetosphere. These are
(1) the cusp region, where particles can move down magnetic field lines, even
into the ionosphere and upper atmosphere, and (2) the equatorial flank regions
in the tail of the magnetosphere where plasma enters the plasma sheath. It
is these particles in the tail that can, during magnetospheric substorms, be

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"precipitated" into the high latitude auroral region and some of them injected
into the inner magnetosphere trapping region where they form the quiet and
disturbed time ring current systems.

Section 3

WORK PERFORMED DURING CURRENT CONTRACT PERIOD

The work performed during this last contract period had to do with the other
extension of the original model, to make it valid for periods of disturbed
magnetic conditions. (The earlier models are all valid for tilted conditions
but only for quiet magnetic conditions.) Another problem with the models
to date was that they have been represented in series form, but for all three
current systems, simultaneously. Thus the input to the model might be the
location of the point where the magnetic field is required and the tilt angle,
and the output of the model would be the three vector components of the total
magnetospheric magnetic field at that point. However, during disturbed
periods, the magnetopause ring and tail current systems quite obviously change
their strengths and locations at least some of the time quite independently
of each other. Therefore it was required to go back to the original work on
determining the magnetic field from each of the current systems, and ultimately
obtaining a description of the three components of each of the current sources
separately. Other problems with the description of the distributed currents
using wires and the need for a representation which permits $\nabla \times \bar{B}$ to be non-zero,
had already been dealt with.

3.1 DISTURBED FIELD EXPANSIONS

The procedure then was as follows. The magnetic field was re-determined for
each of the three current systems separately with appropriate spacing of the
points throughout the magnetosphere and special attention given to the nose
and distant tail regions. Each component was then used for each of the three

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current systems to obtain nine separate expansions. It is mentioned that
some of these expansions were much more difficult to obtain than others, owing
to the geometries involved and the difficulty of correctly fitting some of the
magnetic field components. The series were chosen to minimize the errors and
with each series fit, a comparison was made at each point between the input
raw data and the computed least squares best fit. The average errors over all
nine components distributed throughout the magnetosphere is on the order of
8 percent. That is, the field at any one point has an error in each component
no larger, on average, than 8 percent at any point throughout the magnetosphere.
Most of the large percent errors occurred farther down the tail, where the total
actual field is typically smaller than 1 gamma. Thus, the absolute errors
are not large and over most of the magnetosphere are less than 2 gamma.

3.2 DISTURBED FIELD TOPOLOGY

The changes in magnetic field topology resulting from variation in the
strengths of the three major magnetospheric current systems are now described.

It is useful in the testing of magnetic field models to compare their outputs
with the observed ΔB contours. ΔB is the magnitude of the contribution of the
magnetospheric field to the total observed field. By symmetry in the present
model ΔB along the sun-earth line is the same as the B_Z component of the field
(in the coordinates used, the X axis points toward the sun, the Z axis is
coparallel with the dipole and rotation axes and points north, while the Y
axis is directed into the dusk meridian plane). Sugiura and Poros (1973)
have published observed ΔB contours. However, their data are averaged over all
tilt angles as discussed earlier. We have found that this is not the same
as determining the zero-tilt value separately from the current system. With

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this caution in mind, a comparison is made between the observed ΔB values along the sun-earth line and those obtained from the model for various strengths of the three magnetospheric current systems. Generally all of these ΔB plots share the following features: the value of B_Z is largest as the nose of the magnetosphere is approached. This is because of the proximity to the magneto-pause currents flowing in that region which adds to the existing field. The largest depression in the field occurs in the vicinity of the ring current and exhibits minima at about $\pm$ $4R_E$ with the largest on the night side. In the tail of the magnetosphere, B_Z is a small positive number. It is small because the tail is extended. It is positive because the field lines close through the equatorial plane in the north direction. In Figure 9 two curves are given for varying strengths in the tail - nominal and strong with the strong value represented by currents 25 percent above the nominal value. It is seen that the B_Z value in the tail along the sun-earth line does not vary appreciably, the largest effects occurring in the near earth region (there are appreciable changes in the strength of the tail lobe field also which are not shown in the figure).

A picture of the field lines in the noon-midnight meridian more graphically illustrates the effect of changing the strength of the tail current system. The nominal field configuration is shown in Figure 10. The field lines are depicted in 1° intervals from latitude 70 to 74 and then continuing at 2° intervals to the poles in the midnight meridian. The lines are given in 2° intervals from 70 to 90° in the noon meridian. It is seen that the 72° field line goes back to 25 R_E and the 74° line closes beyond lunar orbit. Thus, the nominal field in this model is much less dipolar in structure than previous models. No attempt has been made to force all of the field lines to be closed.

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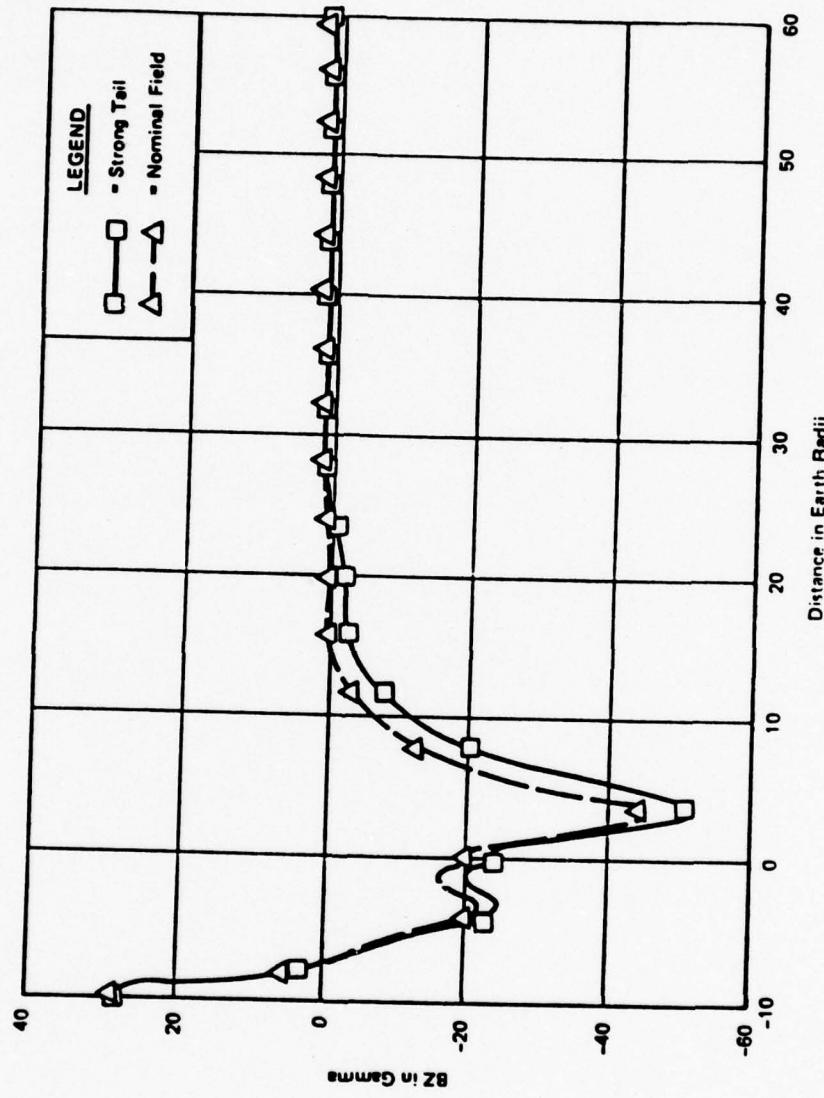
Figure 9. The combined field of the boundary ring and tail currents along the sun-earth line (with only a B_Z component because of symmetry) is shown for nominal conditions and for a strong tail current system.
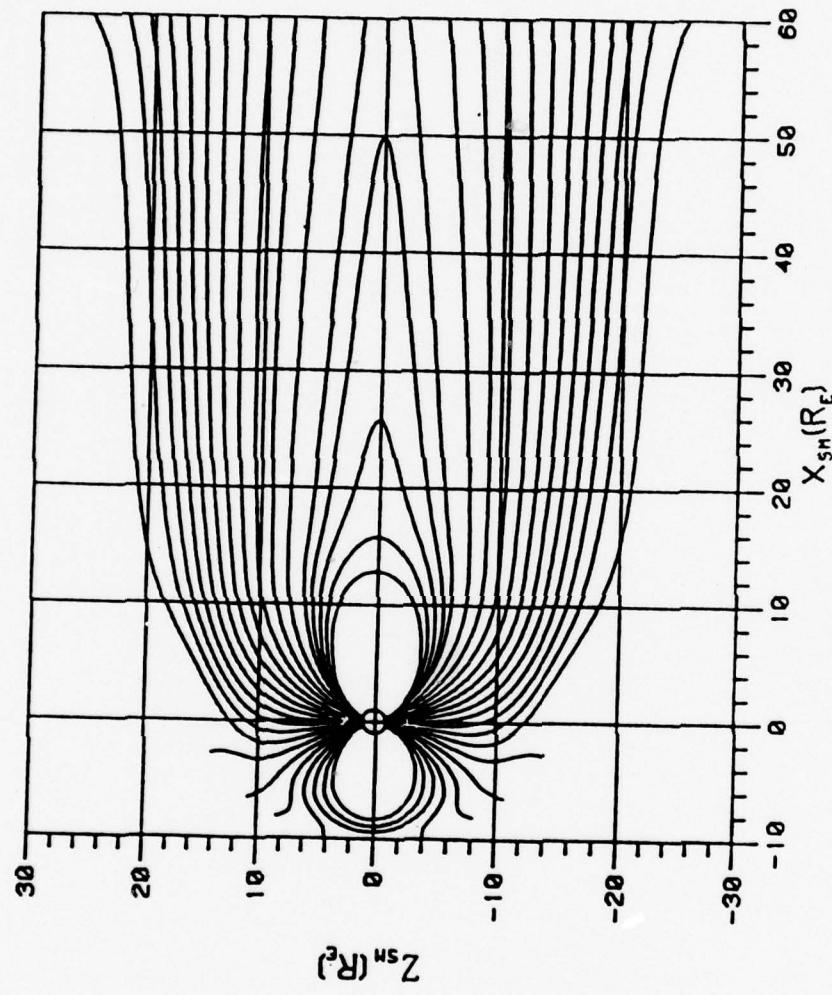
Figure 10. Nominal field line topology in the noon-midnight meridian plane.

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Also the model is self-consistent only in that the final magnetic field values have been compared with observations and found to be in good agreement. The magnetopause currents and shape, however, have been determined with the usual internal dipole field geometries and not self-consistently with the contributions from the magnetospheric currents included. The bell-shaped field lines at lunar orbit for large $|Z|$ values are caused simply by the fitting procedure. The field in that region is not accurately represented.

In Figures 11 and 12 the field topology for weak and strong tail fields are given. In each the nominal values for the ring and magnetopause currents have been used. These configurations we believe come close to describing the state of the magnetotail during the extremes of the substorm process. Notice that when the tail field is large, the 70° field line already extends to about 16 R_E and the 72° line closes beyond lunar orbit. Thus, a change in tail current strength from minus to plus 25 percent of the nominal value changes the extent of the 72° line by about 48 R_E. When such a change occurs during a substorm in an interval of less than one hour, the associated induced electric field is several millivolts per meter and can act to move and accelerate the magnetotail plasma.

In Figures 13 through 15 field lines at 69, 72, 75° magnetic latitude are shown for varying strengths of the tail magnetic field (0.7 to 1.4 of normal in steps of 0.1). The equatorial crossing of the 69° latitude field lines varies nominally but does not move the line into the tail region where the dense plasma sheet particles persist. The 72° line, however, has its equatorial crossing position always in the plasma sheet region. At the other extreme the

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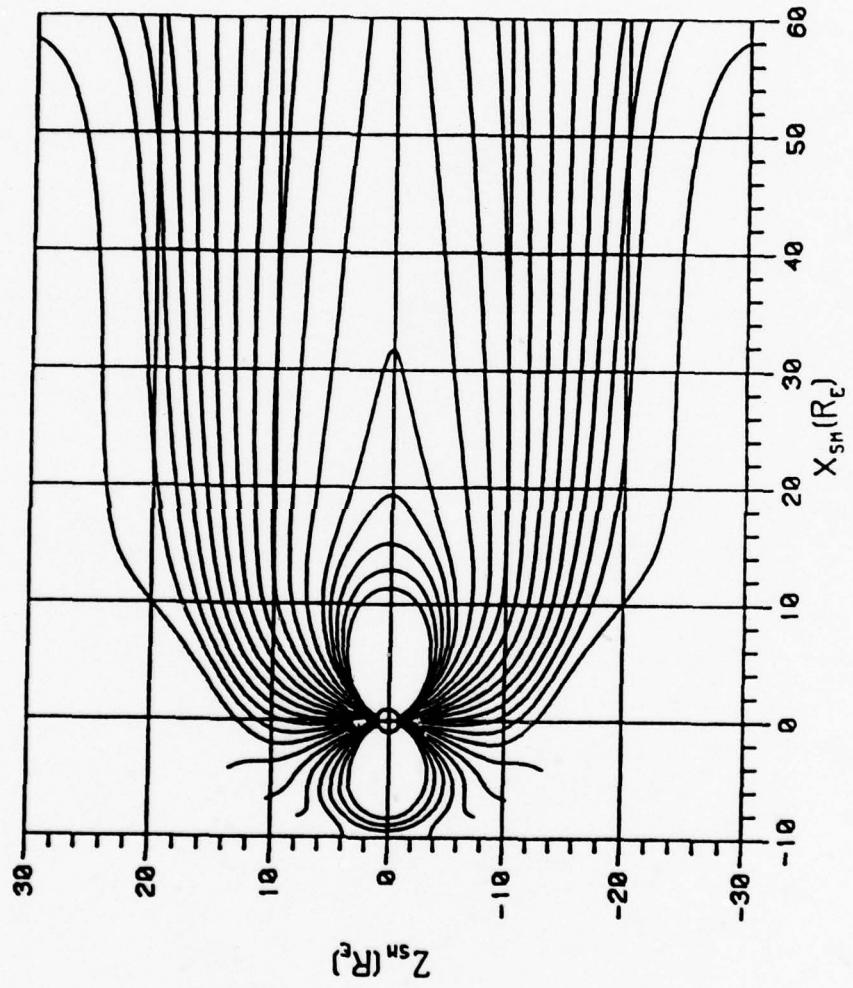
Figure 11. Total magnetic field with a weak tail field and nominal ring and boundary current strengths.

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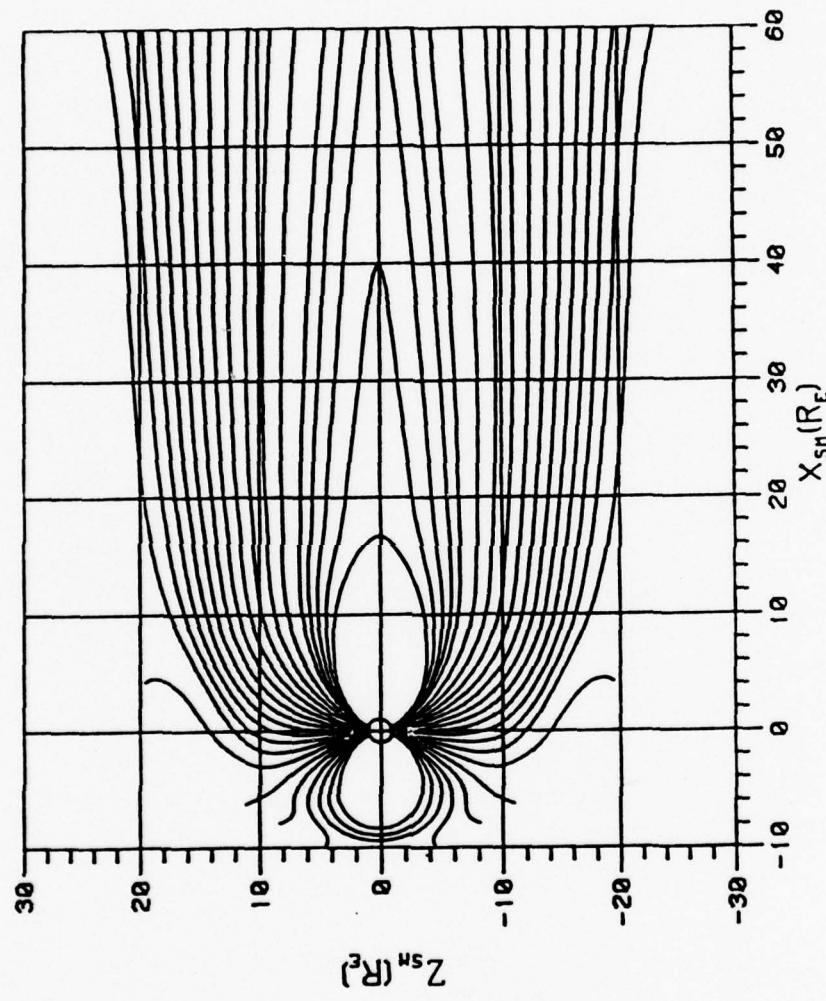
Figure 12. Total magnetic field with a strong tail field and nominal ring and boundary current strengths.

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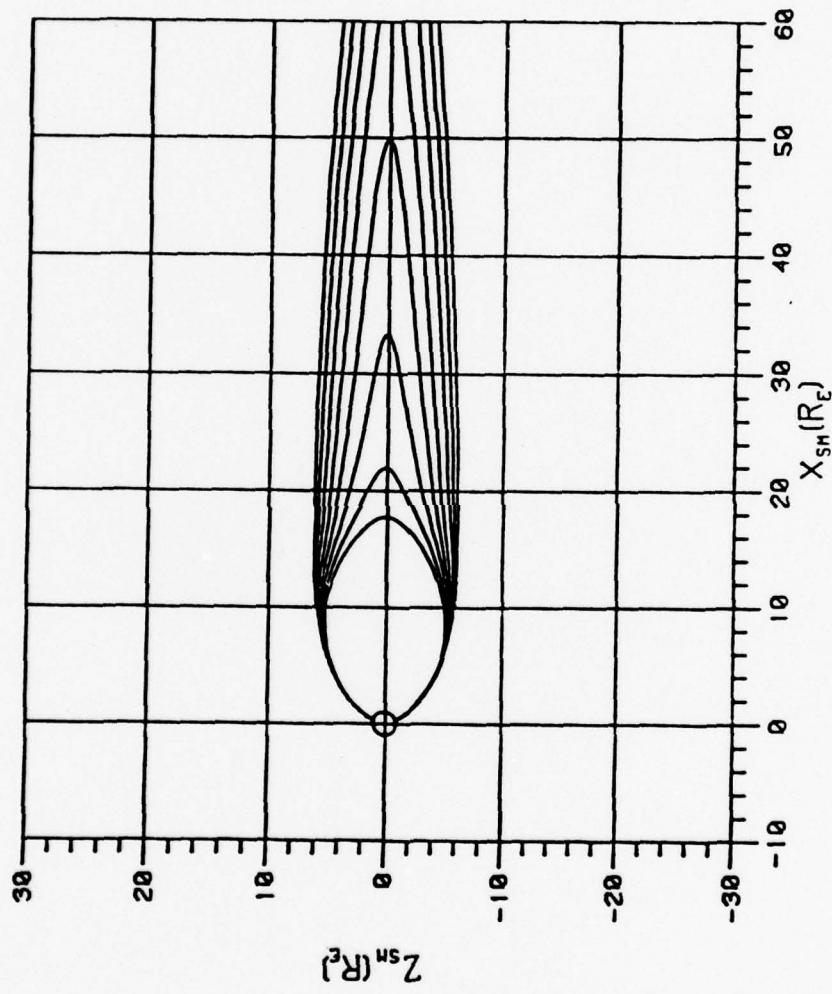
Figure 13. Field lines on the midnight meridian at 69° magnetic latitude for varying tail field strengths.

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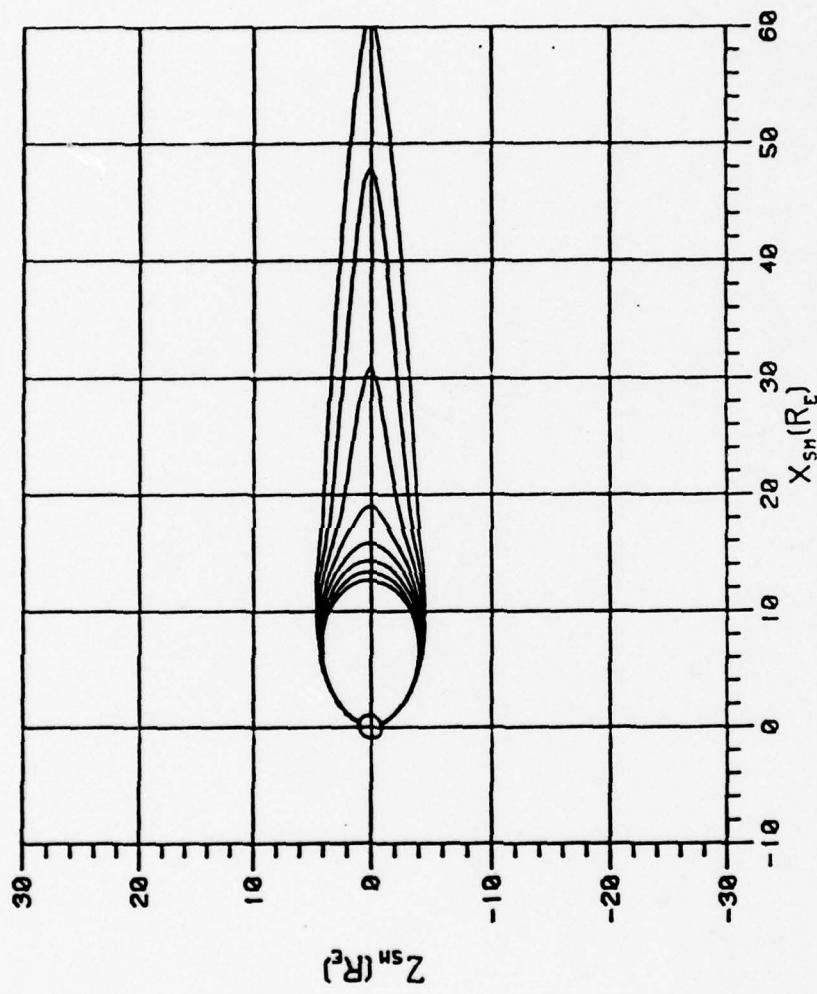
Figure 14. Field lines on the midnight meridian at 72° magnetic latitude for varying tail field strengths.
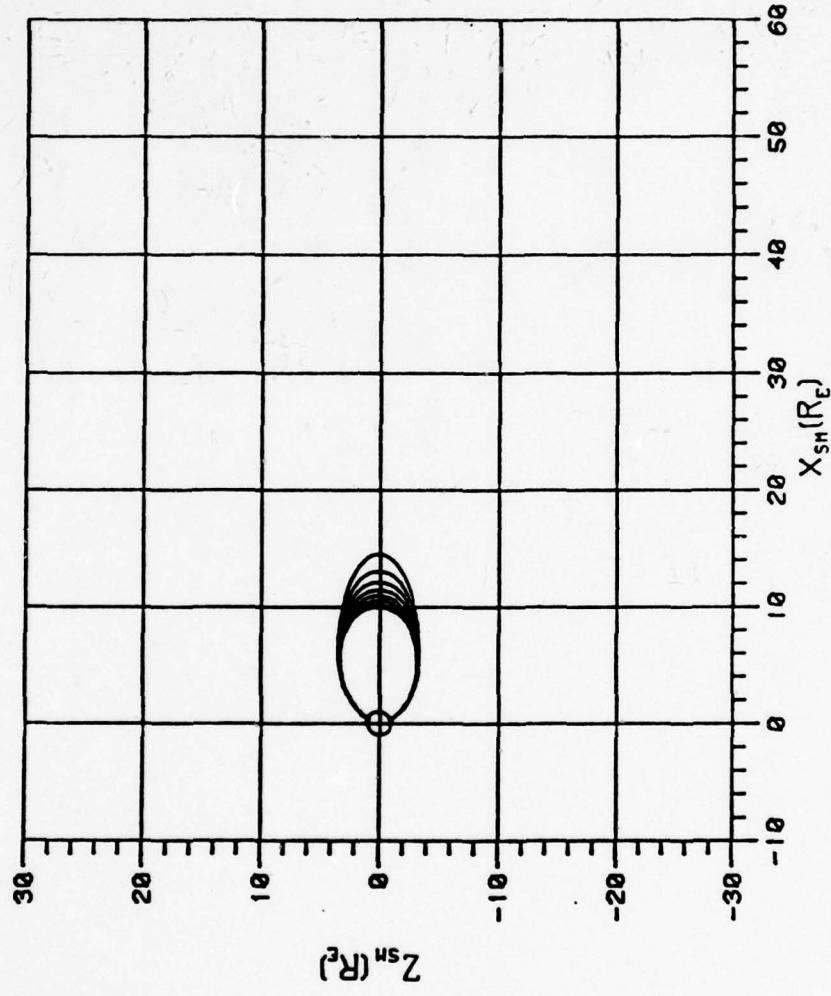
Figure 15. Field lines on the midnight meridian at 75° magnetic latitude for varying tail field strengths

75° line for most strengths of the tail field closes beyond lunar orbit in a region where the particle densities are low. This study of field line extent confirms what we already know from observations concerning the extent of the auroral region (from about 70 to 74° magnetic latitude). Below 70° the field lines are quite rigid while above 75° the lines extend to the distant tail where the plasma density is quite low. In-between (in the auroral region) the field lines are influenced strongly by changes in the strengths of the tail currents and the resultant electric fields can act more readily to influence the behavior of the plasma on the lines.

In Figure 16 the changes in B_Z along the sun-earth line are again shown - this time for a strong ring current. The increased depression in the field just within geosynchronous orbit is apparent. Such a signature should persist during the first day or two of the main phase decrease associated with a magnetic storm. These variations produce an electric field which is large enough to influence charged particle motions in the inner magnetosphere.

3.3 CORRELATIONS OF CALCULATED MAGNETIC VARIATIONS WITH OBSERVATION

As was mentioned earlier, the original model had neither tilt nor disturbed condition provisions built in. The first extension was to include tilt effects. The current work now allows the model to represent disturbed conditions. However, the current model does not include simultaneously both tilt and disturbed conditions but rather attempts to model disturbed conditions only for the symmetric magnetosphere, i.e., the zero tilt configuration.

With this new tool, it is possible to change the location and the strengths of each current system separately. The mere existence, however, of these nine

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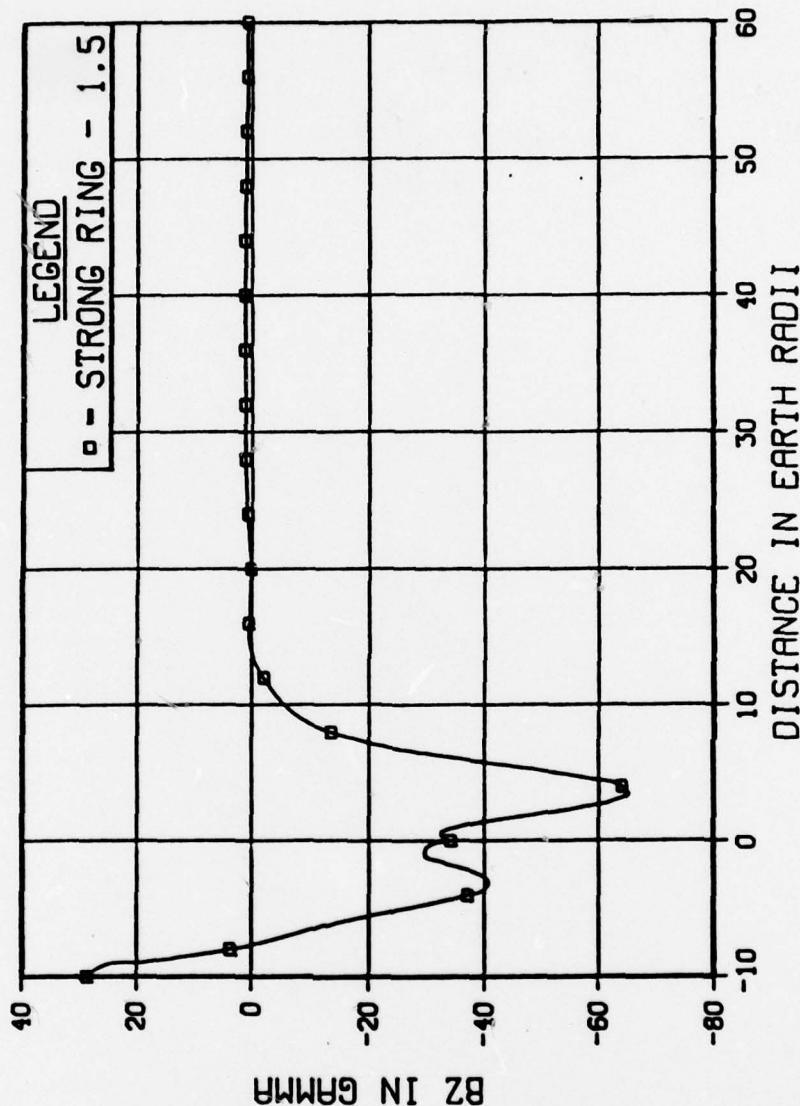
Figure 16. The combined field of the boundary ring and tail currents along the sun-earth line (with only a B_Z component because of symmetry) is shown for a strong ring current system.

series representing the components of each of the three current systems does not yet constitute a disturbed model. It is necessary once more to go back to ground base and satellite magnetometer data in order to compare model results with observations and come up with a time history of the strengths and locations of the various current systems in the magnetosphere, thus it is necessary to obtain a "template" which describes this time history of the different current systems of the magnetosphere as they produce a particular magnetic signature.

This procedure was followed for determining both the sudden commencement part of a magnetic storm and the subsequent main phase depression and slow recovery. In Figure 17 a classical sudden commencement followed by a main phase as observed by mid-latitude station is shown. During the sudden commencement the boundary of the magnetosphere is pushed in to 8 R_E in a span of 15 minutes and the boundary current strengths are increased to maintain pressure balance. At the start of the main phase (time = 0) the inward boundary motion is stopped and the boundary is allowed to slowly relax to its quiet time position. At the same time the ring current strength is increased slowly to a maximum of 5 times normal. The resultant magnetic signature very closely resembles a "standard" sudden commencement and main phase. These results were first presented at the Chapman conference on Quantitative Modeling of Magnetospheric Processes in La Jolla last Fall. Further work on these disturbed models was discussed at the San Francisco American Geophysical Union meeting last December. The definitive model for the sudden commencement and main phase magnetic storm, and additional models of the magnetospheric substorm using this flexible current system tool will be presented at the Spring American Geophysical Union meeting in June.
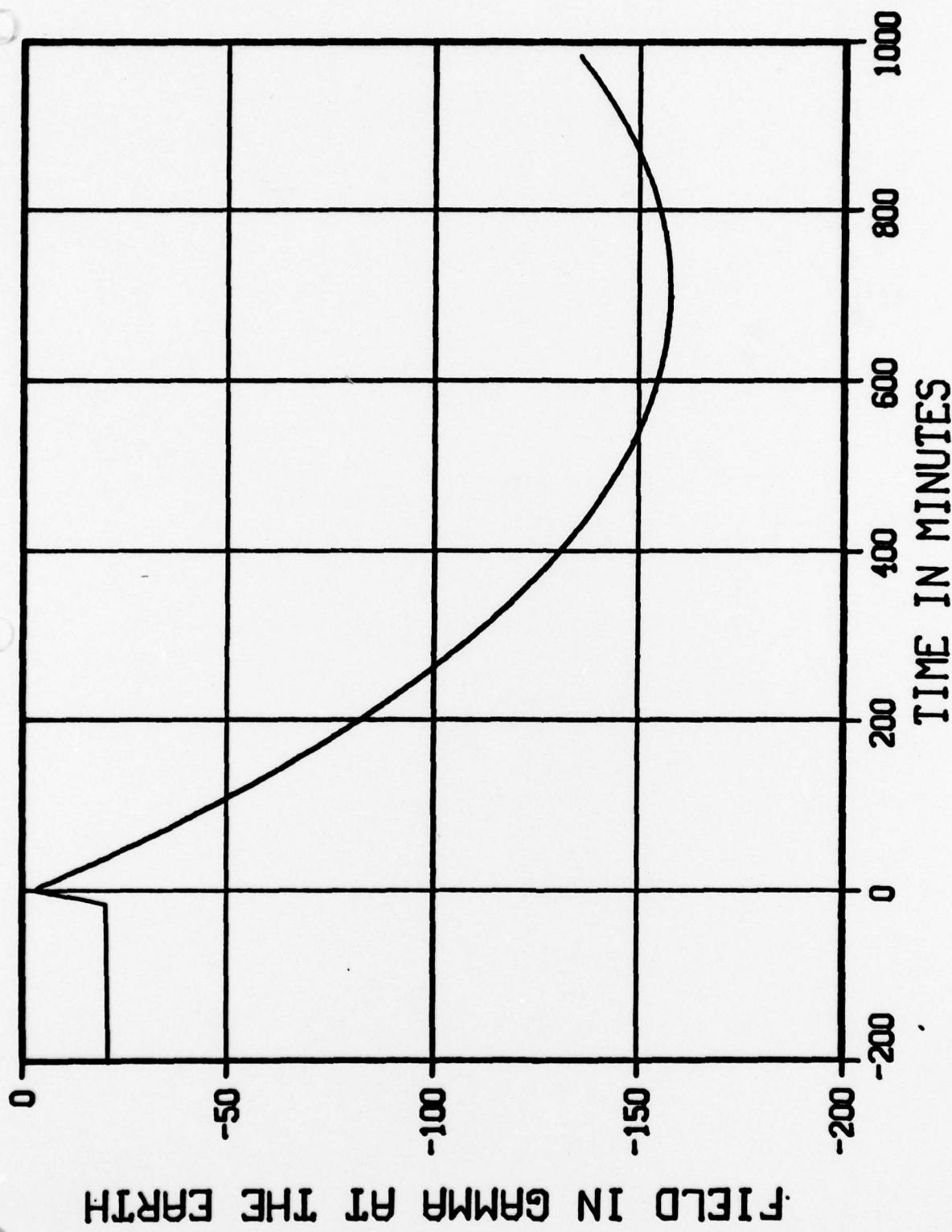
Figure 17. Sudden commencement – boundary compressed to 8 R_E main phase – ring increased to 5 times normal tail current not modified.

Section 4

COMMENTS AND CONCLUSIONS

The process for developing these quantitative models has been at times painfully
slow. It has been difficult for us on several occasions to sit quietly and
listen to arm waving discourse of conjectural models. Nevertheless, our
progress has been rewarded by a quantitative understanding of at least several
magnetospheric processes. We have also been made to feel our efforts have been
worthwhile by the many requests for these models and their associated computer
codes. Currently, we have had just under one hundred requests for these models.
In addition, we know of a few dozen instances where users of the models have
obtained them from the National Space Sciences Data Center or from other
institutions where we have sent a copy of a particular model.

Our goals have been to both understand quantitatively several magnetospheric
features and processes, and at the same time provide to a wide user community,
tools which could be used immediately to help meet their needs. We feel that
these modeling efforts have played an important role in our current quantitative
understanding of the quiet time magnetospere. We would hope that the effort
just completed will be used by many researchers in their efforts to quantita-
tively understand dynamic processes occurring in the magnetosphere. We are
already working closely with the Rice University group and other institutions
on this problem. The disturbed magnetic field model is already an important
input for the work which is underway to describe simultaneously the low

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energy plasma and electric and magnetic fields occurring in the magnetosphere. In particular, we hope that these quantitative models will be useful in the description and understanding of the magnetospheric substorm processes and its relation to ionospheric and auroral substorm phenomena.

An important by-product of this magnetic field work (and, in fact, one of the motivations for it) is the study of electric fields which are induced by time variations in the magnetic field. In all but the original model, we have routinely determined the vector magnetic potential, $\overline{A}$, at the same time as the magnetic induction field was being calculated. A knowledge of the variations in $\overline{A}$ with time directly yields the induced electric field associated with the time varying magnetic field. This electric field is, of course, important in the study of low energy charged particles dynamics in the magnetosphere.

Both the currents and the magnetic fields in the magnetosphere are strongly linked to the earth's upper atmosphere. Changes in these current systems result in variations in the earth's surface magnetic field. These are monitored in terms of magnetic indices, such as K_p, D_{st}. It is accepted that at least part of the quiet time daily variations of the earth's surface magnetic field, S_q, is also produced by currents flowing in the magnetosphere. Thus, these magnetic field models are also of some historical significance as they can be used to help describe some of the variations of the earth's surface magnetic field. The study of the S_q variations was one of the motivations for postulating the existence of the ionosphere. It is a curious fact that the magnetosphere current systems produce all of the features observed in the S_q pattern, (general

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form of the daily variation at all latitudes, the longitudinal structure, and
the seasonal variation), but these variations are only about 15 to 20 percent
of the observed amplitude.

With these and other considerations in mind, it is easy to feel that this work
has been highly worthwhile and it has also been enjoyable. It is hoped that the results
from these models and the set of models themselves will form the basis for
additional work, which will be carried out by many magnetospheric physicists
in their quest to further quantitatively understand those processes that control
the dynamics of the magnetosphere.

Several quantitative models of the earth's magnetospheric magnetic field have
been developed. During the last contract period of performance, the first
quantitative model of the disturbed magnetospheric magnetic field was completed.
It is valid over the entire magnetosphere from the subsolar region to beyond
lunar orbit from the tail. In it, the contributions to the magnetic field from
the three major magnetospheric current systems, the magnetopause, ring, and tail
current, are represented separately. As such, their strengths and locations
may be varied in order to describe either generically or specifically magnetic
"events" occurring in the magnetosphere. The model is restricted only in that
it is developed for the symmetric magnetosphere (the solar wind taken to be
incident perpendicular to the dipole axis). "Templates" for both the sudden
commencement of the classical magnetic storm and the storm time main phase
magnetic field have been described. The development of such templates is
difficult and requires the careful study of both satellite and ground based

magnetometer data.   The template itself consists of a time history of both the location and strengths of the three major magnetospheric current systems. These models are necessary for the self consistent study of the interactions of the low energy plasma in the magnetosphere with the magnetospheric magnetic and electric fields.   Cooperation with other groups has begun to insure that the models will be used for this purpose.

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Appendix A

PUBLICATIONS AND PRESENTATIONS DURING THE PAST YEAR'S PERIOD OF PERFORMANCE

1. Olson, W. P., K. A. Pfitzer and G. J. Mroz. Modeling The Magnetospheric Magnetic Field. Presented at Chapman Conference on Quantitative Modeling of Magnetospheric Processes. La Jolla, 1978, to be published in AGU monogram series.

2. Pfitzer, K. A. The Effect of Magnetic Field Models on Cosmic Ray Cut-off Calculations. Presented at Chapman Conference on Quantitative Modeling of Magnetospheric Processes. La Jolla, 1978, to be published in AGU monogram series.

3. Olson, W. P., K. A. Pfitzer, G. J. Mroz. Locally Induced Acceleration of Low Energy Particles. EOS, 59, 1173, 1978.

4. Pfitzer, K. A., W. P. Olson, G. J. Mroz. The Disturbed Magnetospheric Magnetic Field. EOS, 59, 1169, 1978.

5. Olson, W. P. and K. A. Pfitzer. The Representation of the Time Varying Magnetospheric Electric Fields. To be published at the 1979 Spring AGU Meeting in Washington, D.C.

6. Pfitzer, K. A. and W. P. Olson. The Time Varying Magnetic Field. To be presented at the 1979 Spring AGU Meeting in Washington, D.C.

7. Olson, W. P. A Chapman Conference on the Quantitative Modeling of Magnetospheric Processes. To be published in EOS, 1979.

Appendix B

THE DETERMINATION OF THE DISTRIBUTED MAGNETOSPHERIC CURRENTS

The tail currents and the quiet time ring current are known to be produced by the drift of electrons and ions in opposite direction in the nonuniform total magnetospheric field $\overline{B}$ and by diamagnetic currents caused by gradients in the plasma density. Because these currents persist throughout the magnetosphere, they have been referred to here simply as 'distributed currents.' Here $\overline{B}_D$ refers to the magnetic field associated with both the tail and the quiet time ring current systems.

The strength of the distributed currents, $\overline{J}_D$, is related to the plasma energy and density, and so it is expected that the currents should be strongest in the plasmasphere and through the plasma sheet in the tail of the magnetosphere. The diamagnetic currents are strongest where large gradients in the plasma density occur, i.e., near the plasmapause and the edges of the plasma sheet 2-4 R_E above and below the magnetospheric equatorial plane.

The magnetic observations used to model $\overline{B}_D$ were divided into two regions of the magnetosphere, the lobes and center of the tail, and the inner magnetosphere. The tail observations consist of data that describe the decay of the field in the lobes of the tail with distance down the tail and the decay of the northward component B_z, at the center of the tail, with distance down the tail. In the inner magnetosphere the analysis of Ogo 3 and 5 magnetometer data provided important information on the currents produced by trapped particles. In particular Sugiura, et al. developed contours of constant ΔB; ΔB is the scalar difference between the magnitude of the total observed field B and the magnitude

of $\overline{B}_{DIPOLE}$. Thus their ΔB plots provide an indication of the scalar magnitude of the field produced by currents flowing in the magnetosphere. A fair amount of the ΔB structure can be explained in terms of the diamagnetic currents that flow eastward around the earth out to the vicinity of the plasmapause (because of the increase in plasma density with increasing geocentric distance) and then reverse and flow westward out to the day side magnetopause.

The general form of the currents was used to select the position of 'wires' and the strength of the current flowing through each of them. The field $\overline{B}_D$ was determined only at points distant from the wire (over 3 times the spacing between the wires) or at points between wires that were selected so as to cancel the contributions of the two nearest wires. This procedure for determining $\overline{J}_D$ then yields values of $\overline{B}_D$ that can be compared with observations. Differences in the observed and computed values of B were noted, and changes made in the positions and strengths of the currents in order to decrease the differences. The final model of $\overline{J}_D$ was then used as input to a model of $\overline{B}_D$. In the paper by Olson and Pfitzer (1974), $\overline{B}_D$ is represented analytically. The current $\overline{J}_D$ is also given analytically, expressed as the curl of $\overline{B}_D$.

To determine $\overline{J}_D$ quantitatively, the inner magnetosphere and the tail were considered separately. Several attempts were made at fitting the lobe and equatorial tail fields with the standard 'theta' current loops. With the cross-tail currents constrained to a thin equatorial sheet it was not possible to model both the lobe and the equatorial fields simultaneously. <u>A good fit was obtained only when the cross-tail currents were allowed to flow throughout the plasma sheet.</u>

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The quiet time ring currents are quite different from those in the tail in that the particles that form them are trapped in the total field $\overline{B}$. These currents were also represented as flowing in wires. None of the current loops exhibit azimuthal symmetry. All cross the earth-sun line at larger distances in the tail than the day side magnetosphere. The currents near the earth flow in an eastward direction and are necessary in order to make Dst at the earth have a reasonable value. The currents continue to flow eastward out to the vicinity of the plasmapause. Near the plasmapause the plasma density decreases rapidly with geocentric distance, giving rise to a strong westward current. At still larger distances, particle drift currents that flow westward around the earth make a significant contribution to $\overline{J}_D$. Thus the currents in the larger ellipses are made to flow westward. The values of $\overline{J}_D$ computed from the analytic model of $\overline{B}$ which used $\overline{B}_D$ as input are shown in Figure B-1. They are in good agreement with the input values obtained by integration over the wires.

Magnetosheath plasma flows across the tail of the magnetosphere and contributes simultaneously to the plasma sheet and the distributed currents in the tail. This penetration of magnetosheath plasma suggests that the magnetosphere is 'open' to low-energy particles over several regions of the magnetopause. In the discussion of the open versus 'closed' magnetosphere models, reference is usually made to the magnetic field configuration and whether the near-earth field is connected to the interplanetary field. This question is usually asked not so much because there is an interest in the field configuration for its own sake but because this configuration has important consequences for the entry of solar wind and cosmic ray particles into the magnetosphere. This work

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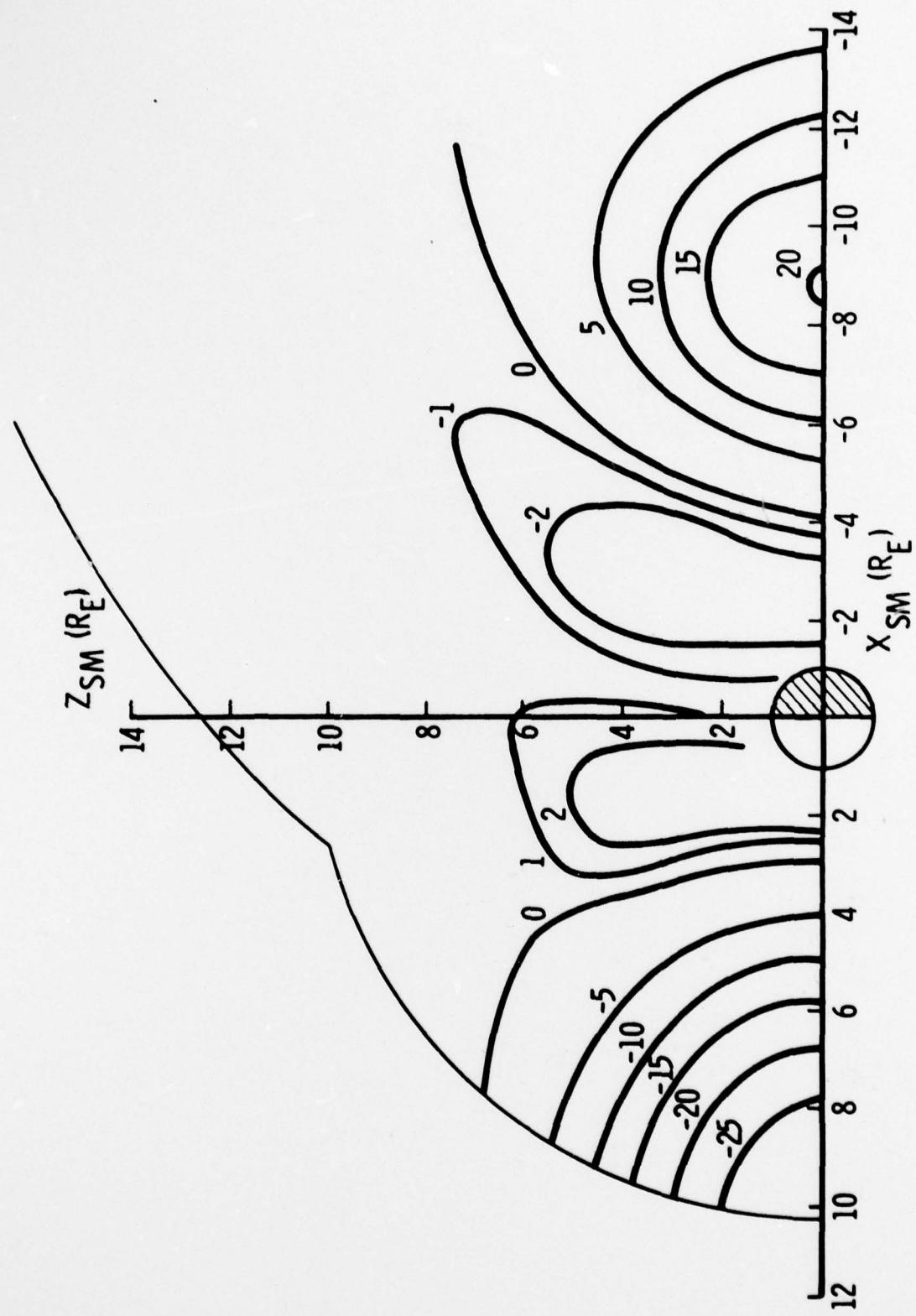
Figure B-1. Contours of constant distributed current density in the noon-midnight meridian plane as obtained from $\nabla \times \overline{B}$. To obtain current densities in amperes per meter^2 multiply the labeled contour values by 1.24×10^{-10}.

suggests that both high- and low-energy particles enter the magnetosphere even if the magnetosphere is magnetically closed. When plasma and field properties are considered self-consistently, the day side cusps are formed, and it is not possible to confine the geomagnetic field. It is probable that it is then also not possible to confine $\overline{B}$ to the magnetosphere in the equatorial regions of the tail. Thus although the details of the merging of the geomagnetic and interplanetary fields have not been studied quantitatively. These studies suggest that the magnetosphere is always open to the entry of charged particles and that in any self-consistent quantitative model of magnetospheric particles and fields $\overline{B}$ will not be completely confined.